

Gamma-ray burst: probe of a black hole

Wei Wang and Yongheng Zhao

National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012

wwang@lamost.bao.ac.cn

Received _____; accepted _____

ABSTRACT

There is strong evidence for the existence of black holes(BHs) in some X-ray binaries and most galactic nuclei, based on different measuremental approaches, but black holes aren't finally identified for the lack of very firm observational evidence up to now. Because the direct evidence for BHs should come from determination of strong gravitational redshift, we hope an object can fall into the region near the BH horizon where radiation can be detected. Therefore the object must be compact stars as neutron stars(NSs), then the intense astrophysical processes will release very high energy radiation which is transient, fast-variant. These phenomena may point to gamma-ray bursts(GRBs) observed. And recent observations of iron lines suggest that afterglows of GRBs show the similar property in active galactic nuclei(AGNs), implying GRBs may originate from intense events related to black holes. In this letter, a model for GRBs and afterglows is proposed to obtain the range of gravitational redshifts(z_g) of GRBs with known cosmological redshifts. Hence, we provide a new method that with a search for high-energy emission lines(X- or γ -rays) in GRBs, one can determine the gravitational redshift. We expect $z_g > 0.5$ or even larger, so that we can rule out the possibility of other compact objects such as NSs, suggesting that the central progenitors of GRBs should be black holes.

Subject headings: black hole physics – accretion, accretion disks – gamma-rays : burst

1. Introduction

The approaches to search for observational evidence for the existence of black holes are provided with the various measuremental methods, such as stellar dynamics (Ghez et al. 1998, 2000), optical emission lines from gas disks (Ferrarese, Ford & Jaffe 1996; Macchetto et al. 1997), water maser disks (Miyoshi et al. 1995), X-ray lines (e.g. Fe $K\alpha$ line, Nandra et al. 1997) and the strength of ultrasoft component of X-ray spectra (Zhang, Cui & Chen 1997). However, all these methods are only related to gaseous processes where (at least two gravitational radius) the gravitational field is weak. To probe the very strong gravitational field, the radiation should result from the process near the BH horizon where a large number high-energy photons can be released. If the high-energy emission lines are identified, we can determine the large gravitational redshift. Here, we propose that GRBs may be the best approach.

Our method is partly motivated by the recent observational evidence for the existence of Fe $K\alpha$ lines in the X-ray afterglows of GRB 990705 (Amati et al. 2000), 990712 (Frontera et al. 2001), 991216 (Piro et al. 2000) and 000214 (Antonelli et al. 2000), and in fact, GRB 970508 (Piro et al. 1999) and 970828 (Yoshida et al. 1999) have also shown the evidence for the iron lines. According to the observed line fluence, the mass of iron should account for about $10^{-4} - 0.1 M_{\odot}$, where M_{\odot} is the mass of the sun, which contradicts with the standard fireball model for GRBs because not enough iron in the interstellar medium can be around the progenitors and if the iron is produced during the bursts, it will involve the famous problem of baryon contamination. To explain the iron lines, some researches have proposed some mechanisms: with the energy injection, only a small mass of Fe is required (Rees & Mészáros 2000) and Fe comes from supernova which requires that supernova explosion precedes the GRB event by several months to years (Antonelli et al. 2001).

However, the existence of iron lines shows us the some similarity of GRB afterglows

to AGNs, implying that the origin of GRBs and their afterglows may be related to black holes and accretion process. In this letter, we propose a model of GRBs, in which the massive black hole captures a neutron star to produce a GRB and a normal star forming an accretion disk to produce the afterglow. Then an alternate mechanism is also proposed to explain the iron line origin: Fe line may come from the disk formed by the normal star.

In the following section, we will give a brief description of our GRB and afterglow model where we will show that some GRBs may be the good candidates of black holes. In Section 3, the method to probe the firm evidence for black holes is provided, summary and outlook are presented in Section 4.

2. GRB and Afterglow Model

Our GRB model is simply described as follows. A massive black hole catches a neutron star, which can produce a large number of γ -ray photons through the intense astrophysical process in a short timescale. In this case, we could observe only the burst. And the minimum variability timescales of burst light curves are related to the NS size, $\Delta t \geq \frac{R}{c}(1+z)(1+z_g)$, of the order of milliseconds which is consistent with GRB observations, where R is the NS radius, c is light speed and z is the cosmological redshift. If a binary (a neutron star and a normal star) rather than an isolated neutron star falls into a black hole, when the normal star is disrupted forming a disk and accreted into the black hole, X-ray and optical radiation are released. Then both bursts and afterglows are observed. Of course, only normal stars captured by black holes in galactic centre will produce flares in optical or X-ray band without bursts, which also may be of observability (Rees 1988, 1990). And our group now is trying to survey those optical flares.

The afterglows will be very similar to the continuum radiation of AGNs, for example,

the spectrum of the afterglow of GRB 970508 (Galama, T.J. et al. 1998a) may like that of a blazar. What’s more, the accretion process can account for the afterglows decaying in time as a power-law. After the tidal disruption of a normal star occurs, two processes will supply mass to the central black hole. The first has been studied by Rees (1988, 1990): the stream of stellar mass strung out in far-ranging orbits, showing that the infall rate declines as $t^{-5/3}$. The other case involves mass loss from the inner edge of the accretion disk. Cannizzo et al.(1990) have discussed this case of late-time evolution of \dot{M} in which the accretion disk supply rate varies as $t^{-1.2}$.

BH-NS interaction has been studied by some previous authors with the numerical simulations (Lattimer & Schramm 1976; Kluźniak & Lee 1998; Janka et al. 1999), which was also taken as one of successful models of GRBs. Here, we also have analyzed the process with simple calculations. Assuming the different masses of black holes, we derived the gravitational redshifts by computing the gravitational radius r_g ($= \frac{2GM}{c^2}$, where G is gravitational constant) and the critical radius r where a neutron star is disrupted by the central black hole through tidal force. In calculations, we suppose the mass and radius of the neutron star are $1.4 M_\odot$ and 10 km respectively. For a comparison, the process is computed with Landau potential (Landau & Lifshitz 1975):

$$\phi = -\frac{c^2}{2}\ln(1 - \frac{r_g}{r}) \quad (1)$$

and pseudo-Newtonian potential (Paczynski & Wiita 1980):

$$\phi = -\frac{GM}{r - r_g} \quad (2)$$

in separation. In Figure 1, two dashed lines have shown z_g as a function of the BH masses according to Landau(up) and pseudo-Newtonian(down) potential respectively. We note $z_g \gg 1$ when masses are very large, implying that massive black holes may be the better test for observations.

From the above analysis, a black hole capturing an isolated neutron stars produces a large number of high-energy photons through a very intense process, which is a GRB observed. With the known total energy of GRBs, we evaluated the gravitational redshift around the critical radius

$$1 + z_g \leq \frac{E_{\text{NS}}}{E_\gamma}, \quad (3)$$

where E_{NS} is the total rest energy of a neutron star and E_γ is the isotropic γ -ray energy. Since $1 + z_g = (1 - \frac{r_g}{r})^{-1/2}$, we can find $r - r_g \sim \frac{r_g}{(1+z_g)^2 - 1}$. Hence, we estimate the duration of a burst,

$$T_\gamma \geq \frac{r - r_g}{c}(1 + z_g) \sim \frac{M}{10^5 M_\odot} \frac{1 + z_g}{(1 + z_g)^2 - 1}, \quad (4)$$

where M is the mass of the black hole, which also tells us the shorter bursts with the smaller central masses. The Equation(1) can give a low limit of z_g :

$$1 + z_g - (1 + z_g)^{-1} \geq \frac{1}{T_\gamma} \frac{M}{10^5 M_\odot}. \quad (5)$$

Then the determination of z_g will depend on our constraint on the masses of black holes.

With Eqs. 3 and 5, we can also give a constraint on the masses of black holes,

$$\frac{M}{M_\odot} \leq 10^5 T_\gamma \left(\frac{E_{\text{NS}}}{E_\gamma} - \frac{E_\gamma}{E_{\text{NS}}} \right). \quad (6)$$

When a binary is falling into a black hole, the normal star will be disrupted to form a accretion disk in the zone far away from the black hole which is very similar to the accretion disks in AGNs, and afterglows in X-ray, optical and radio bands can be produced in the disk from where Fe K α lines are also emitted. We consider a thick disk model, then the radial velocity $v_r \sim \alpha c_s$, where α is the viscosity parameter ($0 < \alpha \leq 1$) and c_s is the sound speed. The viscosity timescale is given by $t_{\text{vis}} \sim \frac{r_*}{v_r} \sim \frac{r_*}{\alpha c_s}$, where r_* is the disk radius. c_s can be estimated from $c_s^2 \sim \frac{kT}{m_p}$, where k is the Boltzmann constant, T is the disk temperature and m_p is the mass of the proton. Since the radiation of afterglows is emitted from the disk, one can find (Frank, King & Raine 1992) $T \geq (\frac{L}{4\pi r_*^2 \sigma})^{1/4}$, where L is the disk luminosity also

the afterglow luminosity, and σ is the Stefan-Boltzmann constant. Therefore, we reach an important result on the masses of black holes:

$$\frac{M}{M_{\odot}} \geq \left(\frac{L}{10^{23} \text{ergs}^{-1}} \right)^{1/10} t_{vis}^{4/5} \equiv M_d, \quad (7)$$

where we have taken $\alpha \sim 1$, and $r_* \sim 3r_g$.

To further test our model, we firstly calculated the isotropic γ -ray energy (E_{γ}) and optical (R band) peak luminosity (L) of 20 well-studied GRBs with known cosmological redshifts (Bloom, Kulkarni & Djorgovski 2000), and derived some intrinsic parameters of GRBs which are displayed in Table 1. In the calculation, we accept the cosmological model with $H_0 = 65 \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, taking $t_{vis} \sim t$, the timescale when the lightcurves of afterglows evolve from the peak flux to the half. With these parameters and above equations, we can estimate the ranges of the black hole masses and z_g in our model. And R band luminosity also gives a check on BH masses using the Eddington luminosity limit:

$$\frac{M_L}{M_{\odot}} \sim \frac{L}{1.3 \times 10^{38} \text{ergs}^{-1}}. \quad (8)$$

Our final results are presented in Table 1 and plotted in Figure 1, in which two dashed lines have been noted above. From Figure 1, we may draw following three conclusions. First, we have found gravitational redshifts of some GRBs are very large: seven GRBs whose gravitational redshifts $z_g > 0.5$, which strongly implies that the central engines of these GRBs should be the best candidates of black holes. Second, the masses of black holes mostly distribute around $10^6 M_{\odot}$ which are comparable to the masses of black holes in the normal galaxies as in our Galaxy. Third, the range of z_g of GRBs calculated is consistent with the range given by two lines, supporting our model.

Because short bursts (with the duration $T_{\gamma} < 2\text{s}$) correspond to the relatively small masses of black holes, radiation from the disk around low-mass black holes will be so faint that it cannot be observed by our optical telescopes. Therefore, our model for GRBs

and afterglows may give a reliable explanation why afterglows cannot be observed from most detected GRBs but only in a very small part with the longer durations. Because in galaxies the number of isolated neutron stars is larger than the number of neutron stars in binary systems according to the observations of pulsars (Taylor, Manchester & Lyne 1993), the possibility of the former captured by black holes will be much larger, implying the afterglows of GRBs are really rare, which is consistent with the observations (Lamb 2000). The different actions between long-duration GRBs and AGNs may result from the circumstance of black holes, since AGNs are in a dirty environment while GRBs in a clean one with a neutron star or binary captured occasionally. We think that our unified model as a possible mechanism of GRBs and afterglows can successfully explain the different occurring rates of bursts and afterglows and the formation of iron lines recently discovered.

3. Searching for Firm Evidence for Black Holes

In the above section, we have applied our model to some GRBs with known cosmological redshifts. In Table 1, we note that some GRBs have very large gravitational redshifts such as GRB 970828 ($z_g > 3.0$), 980425 ($z_g > 1.4$), 000301c ($z_g > 1.9$). Therefore, in our model, these GRB central engines should be the good candidates of black holes. However, to further probe the central body of a gamma-ray burst, we expect that high spectral resolution detectors can find the reliable emission lines in the spectra of GRBs and also suggest that pair annihilation lines (511 keV line) may be the best approach. Hitherto, the emission lines have been detected and identified in the energy spectrum of GRBs by Venera 11 and 12 (Mazets et al. 1981) before 1980 and BASTE (Briggs et al. 1997, 1999) in 1990's. The centroid energies of emission lines distribute in two different ranges, 330-460 and 40-50 keV.

The lines in the broad range of 330-460 keV were interpreted as the strongly redshifted

511 keV annihilation lines, but the emission lines at 40-50 keV were thought to be formed in another process. For instance, GRB 790526 revealed a emission line at 45 keV which was previously thought to be the reliable evidence of emissions at the cyclotron frequency in the surface of a nearby magnetized neutron star (Mazets et al. 1981). However, since the measurement of the redshift of GRB 970508 (Metzger et al. 1997), the evidence for a cosmological distance scale for most or all bursts is confirmed, then GRBs cannot be a local phenomena on the surface of a neutron star. Hence, we need a new physical mechanism to explain the emission lines observed. In this letter, we interpret the emission lines as strongly redshifted 511 keV annihilation lines in the gravitational field of black holes. Supposing the cosmological redshift of GRBs, $z \sim 1$, we calculated the gravitational redshifts of the lines whose centroids are around 50 keV, $z_g \sim 4$ in accordance with our model expectation. Because the gravitational redshift produced by the known compact objects including neutron stars or even possible strange stars cannot be over 0.5, we may make our decision that the central bodies of these bursts are the best candidates of black holes. In fact, the other lines at 330-460 keV observed have the gravitational redshifts in the range 0.1-0.5, which is also very difficultly realized on the surface of a neutron star. Therefore, GRBs may really originate in the region with the very strong gravitational field, where the central progenitors are black holes with the captured neutron stars.

4. Discussion and Summary

Because the iron lines discovered in the X-ray afterglows of some bursts imply the relation between AGNs and GRBs, a possible model of GRBs and afterglows is proposed in the letter. In our model, we can determine the range of gravitational redshifts of γ -ray radiation with the intrinsic parameters of GRBs and afterglows, and we note some of them are very large ($z_g > 0.5$) implying GRBs as probes of ultra-strong gravity of black holes.

However, very firm evidence should come from the identification of GRB line emissions. Through the determination of the very strong gravitational redshift of emission lines, one can identify the central bodies as black holes. Thus, the spectral line observation of GRBs can provide a very powerful evidence for the existence of black holes. Because of the level limit on the present missions, we need more advanced detectors with higher spectral resolutions in future. Here, we hope that recently launched HETE-II and Swift(in 2003) will do much work on the search for GRB emission lines

The model of GRB afterglows in this letter is also used to explain the X-ray flares recently detected in several nearby normal galaxies with the ROSAT data base. Assuming the number of massive stars which can produce NSs through supernova explosion is about 10% of total star number and one supernova event occurs in 100 years, we can simply estimate the density ratio of stars and NSs in a normal galaxy as $n_{\text{star}}/n_{\text{NS}} \sim 1000$. The observations have given the GRB rate $R_{\text{GRB}} \sim 10^{-6} - 10^{-7}/\text{yr/gal}$, so we can approximately obtain the flare event rate $R_{\text{flare}} \sim 10^{-3} - 10^{-4}/\text{yr/gal}$ which is consistent with the theoretical expected tidal disruption rate (Rees 1988, 1990) and the searching results given by ROSAT all-sky survey (Komossa & Dahlem 2001). With the flare event rate and assuming a solar mass is swallowed by the black hole per event, we find that the central black hole masses in normal galaxies can increase at least up to $10^6 - 10^7 M_{\odot}$ (such as the massive black holes in the center of our Galaxy and M31) through the tidal disruption of stars within the Hubble time scale ($\sim 10^{10}\text{yr}$). This conclusion is also important to the formation and evolution of normal galaxies and massive black holes.

Acknowledgments We would be grateful to Mr.Ye Fangfu for the help in the calculations. This research is supported by the National Natural Science Foundation of China.

REFERENCES

- Akerlof, K, et al., 1999, *Nature*, 398, 400
- Amati, L. et al., 2000, *Science*, 290, 953
- Antonelli, L.A., et al., 2000, *ApJ*, 545, L39
- Bloom, J.S., Kulkarni, S.R. and Djorgovski, S.G., 2000, preprint(astro-ph/0010176)
- Briggs, M.S., et al., 1997, preprint(astro-ph/9712096)
- Briggs, M.S. et al., 1999, preprint(astro-ph/9901224)
- Cannizzo, J.K., Lee, H.M. and Goodman, J., 1990, *ApJ*, 351, 38
- Ferrarese, L., Ford, H. C., and Jaffe, W., 1996, *ApJ*, 470, 444
- Frank, J., King, A.R. and Raine, D.J., 1992, *Accretion Power in Astrophysics, Second Edition*, p.5
- Frontera, F., et al., 2001, preprint(astro-ph/0102234)
- Ghez, A.M. et al., 1998, *ApJ*, 509, 678
- Ghez, A. M., et al., 2000, *Nature*, 407, 349
- Galama, T.J., et al., 1998a, *ApJ*, 500, L97
- Galama, T.J., et al., 1998b, *Nature*, 395, 670
- Janka, H.-T., Eberl, T., Ruffert, M. and Fryer, C.L., 1999, preprint(astro-ph/9908290)
- Kamossa, S. and Dahlem, J., in *MAXI workshop on AGN variability*(astro-ph/0106422)
- Kluźniak, W. and Lee, W. H., 1998, *ApJ*, 494, L53
- Lamb, D.Q., 2000, preprint(astro-ph/0005028)
- Landau, L.D. and Lifshitz, E.M., 1975, *The Classical Theory of Fields*, p.253
- Lattimer, J. M. and Schramm, D. N., 1976, *ApJ*, 210, 549

- Macchetto, F., et al., 1997, ApJ, 489, 579
- Mazets, E.P. et al., 1981, Nature, 290, 378
- Metzger, R., et al., 1997, Nature, 387, 878
- Miyoshi, M., et al., 1995, Nature, 373, 127
- Nandra, K., et al., 1997, ApJ, 477, 602
- Paczynski, B. and Wiita, P.J., 1980, A&A, 88, 23
- Piro, L., et al., 1999, ApJ, 514, L73
- Piro, L., et al., 2000, Science, 290, 955
- Rees, M.J., 1988, Nature, 333, 523
- Rees, M.J., 1990, Science, 247, 817
- Rees, M.J. and Mészáros, P., 2000, ApJ, 545, L73
- Taylor, J.H., Manchester, R.N. and Lyne, A.G., 1993, ApJS, 88, 529
- Yoshida, A. et al., 1999, A&AS, 138, 433
- Zhang, S.N., Cui, W. and Chen, W., 1997, ApJ, 482, L155

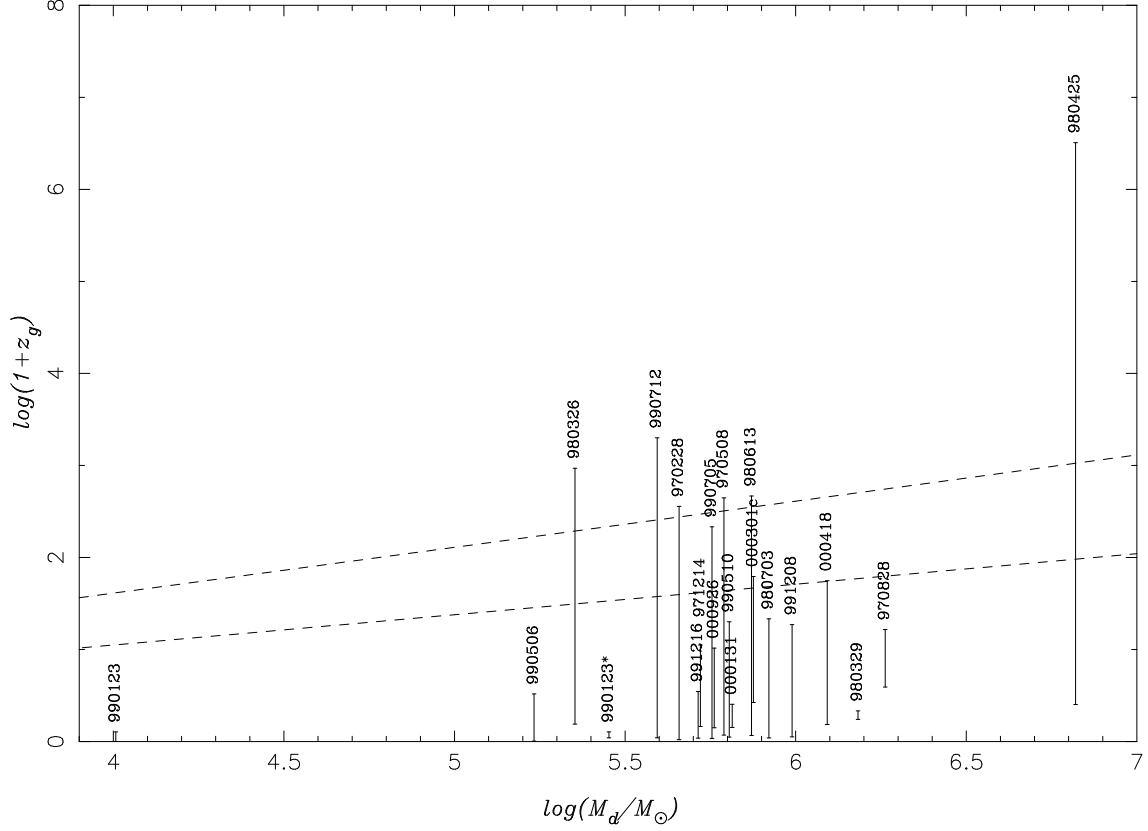


Fig. 1.— The range of GRB gravitational redshifts estimated from our model are plotted as a function of the lower limits of the BH masses. Two dashed lines describe the critical gravitational redshift of neutron stars disrupted by tidal force according to Landau(up) and pseudo-Newtonian(down) potential in separation. 20 GRBs with known cosmological redshifts are displayed, and we noticed most masses distribute around $10^6 M_\odot$ except GRB 980425 and 990123(as noted in Table 1). If we cancel the optical flash and only take the second afterglow of 990123, we note that 990123* which is also plotted in the figure become a normal one similar to others. Refer to the text for details.

Table 1. The intrinsic parameters of 20 GRBs with known cosmological redshifts and derived ranges of black hole masses and gravitational redshifts determined in our model.

name	T_γ (s)	$\log E_\gamma$ (erg)	$\log t$ (s)	$\log L$ (erg s $^{-1}$)	$\log M$ (M_\odot)	z_g	z
970228	47	51.9	4.5	43.2	5.7-9.2(5.1)	0.05-358	0.695
970508	18.7	51.8	4.5	45.1	5.9-8.9(7.0)	0.16-443	0.875
970828	5	53.2	5.0	45.6	6.3-6.9(7.4)	3.0-15.5	0.935
971214	6.8	53.4	4.3	45.8	5.8-6.9(7.7)	0.6-10.2	3.42
980326	2.5	51.5	4.0	44.5	5.4-8.3(6.4)	0.6-1000	1
980329	13	54.2	4.9	45.6	6.2-6.3(7.4)	0.8-1.1	3.5
980425	31	47.9	6.0	45.2	6.8-13.0(5.1)	1.4-3 $\times 10^6$	0.0085
980613	24	51.8	4.7	44.1	5.9-9.1(6.0)	0.16-466	1.096
980703	46	53.1	4.7	44.6	6.0-8.0(6.4)	0.1-20.5	0.966
990123	15	54.3	1.6	50.2	4.1-6.0(12)	0.01-0.3	1.61
990123*			3.5	46.3	5.4-6.0(8.0)	0.15-0.3	
990506	65	53.9	3.7	45.7	5.7-7.3(7.6)	0.05-2.3	1.310
990510	28.6	53.1	4.3	46.6	5.6-7.5(7.5)	0.1-19	1.62
990705	36	52.1	4.7	43.0	5.7-8.9(4.8)	0.1-214	0.25
990712	21	51.1	4.3	45.7	5.6-9.6(6.4)	0.1-2000	0.434
991208	41	53.2	4.7	45.3	6.0-7.9(7.2)	0.15-17.7	0.7055
991216	30	53.9	4.3	45.7	5.7-7.0(7.6)	0.1-2.5	1.02
000131	9	54.1	4.5	45.3	5.8-6.2(7.2)	0.4-1.5	4.5
000301c	3.3	52.6	4.5	45.9	5.9-7.3(7.8)	1.9-61	2.0
000418	14	52.7	4.9	44.7	6.1-7.9(7.6)	0.6-55	1.11854
000926	8.2	53.4	4.3	46.2	5.8-7.0(8.1)	0.4-9	2.066

Note. — The timescales T_γ and t have been divided by a factor $(1+z)$ correction to the GRB intrinsic timescales. Since a particular prompt optical flash (Akerlof et al. 1999) was observed 15 seconds after GRB 990123 stated, we take two cases of the afterglow: the flash($m_R \sim 9$) as a peak and the second afterglow($m_R \sim 17$) as the peak where m_R is the visual magnitude of optical peak in R band. Because of the possible association between GRB 980425 and SN1998sw (Galama et al. 1998b), z is very small making the γ -ray energy too low, and t is very long probably due to the effect of the light curve of SN1998sw. M_L is shown in the brackets, in many cases, it shows a super-Eddington accretion, but some are the sub-Eddington ones.